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SEPARATING AND SEPARATED BOUNDARY LAYERS

Terrence W. Simon
Ralph J. Volino

FEBRUARY 1996

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DOCUMENTATION OF SEPARATING AND SEPARATED BOUNDARY LAYERS

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+ Presently an Assistant Professor at the U.S. Naval Academy

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Abstract

The low-pressure turbine of an aircraft engine operates with a low chord Reynolds number. As such, there are regions of strong streamwise acceleration and diffusion effects. This results in extended regions of transition from laminar to turbulent flow and large zones of flow separation. In response to a need to learn more about the mechanisms that lead to transition and separation in the engine environment, a low-Reynolds-number-flow study was initiated during the Summer of 1994 at Wright Labs. In this project, a low-pressure turbine airfoil cascade was installed in a wind tunnel. To simulate the engine environment, high background turbulence was imposed on the flow and a device for imposing passing wakes upon the flow was fabricated. A program for measurement of the characteristics of the boundary layer; laminar-like or turbulent, separated or attached, was initiated. The Summer project resulted in an effective start on the problem but considerably more remained to be done. This report documents the subsequent work on this project. At the University of Minnesota, an easily accessible facility which had the essential elements of the low-pressure turbine flow was designed, built, and qualified. This facility now provides a convenient means for documenting the flow and developing measurement techniques. The Wright Lab experimental program continued with the completion of the construction, the implementation of the turbulence generating device, and the qualification of the tunnel. Both facilities are now producing data to the program. These data are summarized herein. The University of Minnesota facility has generated pressure profiles for various cases of different Reynolds number and turbulence intensity. The Wright Labs facility has give pressure profiles for various Reynolds numbers. The two facilities are now ready for detailed measurements within the boundary layers.

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DOCUMENTATION OF
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Introduction

Compressor and turbine design models have been moderately successful in predicting losses and heat transfer rates in the high-pressure components of the gas turbine where chord Reynolds numbers, Re_C, are large and separation and transition regions are small. When applied to low chord Reynolds number flows, where long transitional zones and large separation bubbles are present, these models fail. Being able to predict transition and separation under low-Reynolds number operation has recently taken on increased importance for improved designs of gas turbine engines. To illustrate, in the low pressure turbine where the airfoils are aft-loaded, 90% of the blade suction surface can be covered with transitional boundary layer flow (Mayle, 1991). Also, when the chord Reynolds number on an airfoil is decreased, the boundary layer becomes more likely to separate. Separation is expected for Re_C values under 400,000 (Sharma, Ni, and Tanrikut, 1994), although, clearly, there is more to the prediction of separation than the knowledge of Re_C. For instance, elevated free-stream turbulence would reduce the separation Reynolds number. The dependence on turbulence level and scale is presently unknown. The effects of disturbances due to wakes generated by upstream airfoil rows on this separation Reynolds number are even more uncertain. Wakes may result in an instantaneous increase in turbulence level. Also, if the flow were behaving in a quasi-static manner, one would expect wakes to change, momentarily, the angle of attack to an off-design angle, favoring increased separation on the suction surface. Because wakes pass at a high frequency, the quasi-static assumption may be unwarranted. Needed are transient measurements of the boundary layer flow over the downstream portions of the suction surface, ensemble-averaged on the wake passage event. Such measurements provide information about the state of the boundary layer and the receptivity of the boundary layer to external disturbances, including those from the passing wakes. Possible wake generators may be cylinders, representing wake turbulence with large-scale turbulence; thin plates oriented parallel to the flow, representing wakes which consist of decaying boundary layer turbulence; or actual airfoils. Comparisons of measurements in cascades and rotating rigs indicate that losses and heat loads are higher in the unsteady flow than in steady flow (Sharma et al., 1994, Hodson, 1983, Blair et al., 1988, Doorley et al., and Sharma et al. 1990). Sharma et al.,

1994 proposed making such comparisons using scaling on a relative time scale to capture this effect. The appropriate ratio is the wake passage period divided by the transit period for fluid flow through the airfoil row. Cases of similar values of this ratio display similar augmentation due to unsteadiness. Such scaling is applied in the Wright Lab experiment. Operation at low Reynolds numbers would create separation zones, allowing a study of the effect of the wakes on the incipience to the separation process, on the free-shear layer transition length, and on the separation bubble length. Under low-Reynolds-number conditions, upstream wakes can result in smaller separation zones and lower losses relative to steady flow. Presently, no model has been developed to capture this effect (Sharma et al., 1994). Thus, wake effects on the separated flow must be included for a low-Reynolds number study to be accurate and complete. This may be the first experiment with a detailed investigation of the low-pressure turbine flow boundary layer including wake effects. It is important that these tests are done well. Hot-wire anemometry measurements can be made in the free-shear layers over the separation bubbles without affecting the flow. Measurements within the separated flow zone are difficult, but possible, and needed. With these measurements, one could assess whether the change in incidence angle during the wake passing event is important or whether the main wake-related effect is that of turbulence washing over the boundary layer and free-shear-layer flows. Thus, careful documentation of the turbulence and wake disturbance effects is needed in support of design model development.

Objectives

One objective of this program is to coordinate experiments at the University of Minnesota and Wright Labs. to optimize this important test program.

Objectives of the Wright Laboratory Experiment

The objectives of the Wright Lab. program are to determine the transition and separation zone locations for a particular low-pressure airfoil under representative conditions, including an assessment of the effects of free-stream turbulence and of wake passings on the locations of these zones. A secondary objective is to document the pre-separation boundary layer receptivity to external disturbances and the instability of the free-shear layer over the separation zone. In doing so, several representative cases are to be investigated, the transition and separation zones for each are to be located, and measurements are to be taken in the pre-separation boundary layer and in the separation zone. For cases with wakes, this documentation is to be given for various times within the wake passing period.

Objectives of the University of Minnesota Experiment

The University of Minnesota experimental program is configured to support the cascade measurements, but in a simple, single-airfoil test section where probe access is easy and the geometry is more simple. Though a cascade is not used, the flow will simulate most features of the flow in the Wright Lab. cascade, for the curvature and pressure gradient will be replicated. Additionally, the free-stream turbulence will be simulated and the wake passage events will be added in the near future. In this simulated flow, detailed hot-wire measurements will be made to develop a means by which the waveform of the hot-wire time-trace will be used, in conjunction with flow visualization and static pressure profile measurements, to determine the state of the flow. Some turbulent transport terms will be measured in the near-wall region to verify that the boundary layer flow is truly turbulent (contains turbulent production, not just the unsteadiness of the external turbulence in the free-stream), or is free of significant turbulence production. This, we have done over the last six years in similar, attached flows but with constant-pressure boundary layers or with favorable pressure gradients. Extensions of our past techniques will be used in flows with the imposition of an adverse pressure gradient and in the investigations of incipient-to-separation and separated flows. Results from this work will be used by the University of Minnesota and the Wright Lab. researchers in the Wright Lab. cascade facility. Additionally, computational efforts at the Wright Lab. will be made to compute this flow to test present schemes for the prediction of transition and separation on low-pressure turbine airfoil surfaces. The University of Minnesota experiments, the Wright Lab. experiments, and the Wright Lab. computations constitute the overall program. The experiments will provide comparison data for the computations and turbulence data for improvements of the turbulence transport predictions within the computational models. Researchers of the team will be looking for techniques for improving the turbine performance which may come about by reduction of boundary layer separation zones. Thus, results may include improved future turbine designs and improved design models. If the eventual results of this program can lead to even a percent improvement in the engine performance, as they have a strong likelihood of doing, the return on investment for this work is enormous. There is considerable opportunity for payback when working on the low-pressure turbine. It has traditionally not received the level of attention given to compressor or high-pressure turbine blading. The low-pressure turbine has recently been targeted as a section of the engine in need of research attention (Sharma, Ni, and Tanrikut, 1994).

Facilities

The Wright Lab Cascade Facility

The Wright Lab. experiments were conducted in the AFIT cascade facility. This facility has been documented in numerous papers and theses from the Lab. Recent modifications to the facility are documented in the report of Summer 1994 research by Simon and Volino. This wind tunnel is driven with a centrifugal blower operating in the suction mode. Flow velocity control is with a motor controller, with inlet dampers on the fan, and with a bypass vent on the ductwork between the test section and the fan. A plan view of the wind tunnel is given as Fig. 1. The cascade test section consists of four geometrically identical blades of chord length 11.4 cm (4.5 inches).

Turbulence Generator

Upstream of the cascade is a turbulence generation device which consists of a passive square grid of 13 mm by 13 mm (0.5 inch by 0.5 inch) square bars arranged with a 25.4 mm (1.0 inch) center-to-center spacing. This resides 1.5 m (57 inches) upstream of the cascade row. A distance of 0.6 m (24 inches) downstream of the passive grid is an active jet grid with 6 tubes each with 6 blowing holes distributed and oriented as shown in Fig. 2. The passive grid/jet grid arrangement is a replica of one described by Sahm and Moffat (1992). This type of generator was reproduced and installed in the University of Minnesota facility.

Wake Generator

At a distance of 7.6 cm upstream of the leading edge of the cascade row is a series of 6 cylinders which are traversed across the tunnel cross-section in the transverse direction. These cylinders simulate the wakes that are generated by the airfoil row which resides just upstream of the airfoil row of interest in an actual turbine. The cylinders are 9.5 mm (0.375 inch) in diameter and are separated by the same transverse spacing as that of the airfoils, 91.7 mm (3.611 inches). These cylinders are driven by a device which is capable of translating them at selected velocities from 0.5 m/sec to as high as 5.5 m/sec. The total translation distance is 43 cm (17 inches). Attached to the drive mechanism is a photo-diode sensor which indicates when the translation runner has moved a distance of 10 cm (4 inches). The signal from this sensor is used to activate the data acquisition trigger. The duration of the measurement portion of the translation is from one to five wake passings. A similar wake generator is being fabricated for installation in the University of Minnesota facility. Wake passing data should be taken at Minnesota during the Summer of 1996.

The measurement techniques developed at the University of Minnesota have been and will continue to be implemented in the Wright Lab. facility and program. Such implementation will be done by communication with the Wright Lab. group and by the present researchers during visits to Wright Lab.

The University of Minnesota Facility

The University of Minnesota facility is complementary to the cascade facility at Wright Lab. The flow passes through the same turbulence generators as at Wright but then passes through a channel between two curved walls, Fig. 3. The leading edges of the walls are configured to simulate the leading edge/stagnation-line regions of two adjacent blades. The two (suction and pressure) downstream walls are bent and oriented so that the curvature and pressure gradient profiles of the cascade are replicated. The facility has an airfoil aspect ratio of 6, thus, the effects of the endwall flow on the mid span boundary layers are minimal. Also, the simpler geometry of the facility affords easier access for flow visualization and detailed measurements.

About the measurements:

The first measurements, already taken and presented herein, are profiles of surface static pressure. Next, measurements will be taken very near the surface to determine zones of flow reversal. A precursor to this was a program of near-wall measurements to assess the utility of such measurements for the direct computation of wall shear stress and heat transfer coefficient. This is documented in Qiu et al. (1995). More remains to be developed here, however. This development will continue during the Spring of 1996. Because the hot-wire does not discriminate flow direction for a single sample, the entire flow waveform must be recorded. The waveform will have sufficient temporal resolution to show flow reversal among other important events. After the near-wall measurements are taken, the evolution of the attached boundary layer will be documented, including documentation of such turbulence quantities as elements of the Reynolds shear stress tensor. Following this will be a similar study, but applied to the free shear layer over a separated zone. Throughout, flow visualization using smoke injection, oil and lampblack, the ink-dot technique, or the smoke-wire technique, all familiar to our lab, will be used to complement the measurements.

Hot Wire Anemometer

Instantaneous local velocities are measured using a TSI Model 100 (IFA-100) Intelligent Flow Analyzer, constant-temperature anemometer with a TSI Model No. 1210-T1.5 Tungsten single-wire, hot-wire probe, a TSI Model No. 1243-20 platinum cross-sensor, hot-film probe, or a

TSI Model No. 1299BM triple-sensor probe. The cross-sensor probe is used to measure turbulent shear stress. It has two 51 μm (2 mil) diameter sensors, mounted perpendicular to one another, parallel to the cascade endwall, and 45° to the airfoil surfaces. The single-wire sensor is used for indicating the state of the boundary layer on the suction surface of the airfoil by traversing it very near the surface, measuring the fluctuation intensity and interrogating the waveform to detect signs of flow reversal. The single-wire probe has one 4 μm (150 μinch) diameter wire, mounted perpendicular to the flow and parallel to the convex wall. Each hot-wire output signal, an analog voltage, is amplified and filtered using a TSI Model No. 158 signal conditioner. Each is read with a data acquisition unit. The triple-sensor probe is used to obtain 3-D measurements. It has a 90° bend with six straight prongs (see Fig. 4). Three films sensors of 51 μm (2 mil) diameter are mounted perpendicular to one another and with a 35° inclination angle.

Surface Static Pressure

The surface static pressures are read using static pressure ports installed on a wall surface. They are connected to the diaphragm of a Validyne, 860 Pa- (3.5 inch)- maximum-pressure-difference, variable-reluctance, pressure transducer driven by a Validyne model CD-15 Carrier Demodulator. The pressure transducer provides an analog voltage signal which is read with the data acquisition unit.

Temperatures

A single Type E thermocouple is used to record the flow temperatures.

Data Acquisition

All the data acquisition is with a Norland Prowler (now High-Techniques) high-Speed Data Acquisition System. This unit has a 12-bit A/D converter which allows simultaneous sampling of two channels per unit (6 channels in the Lab.). Though the bulk of the Minnesota work will be with the single wire, X-wire measurements may be included to help determine the state, laminar or turbulent, of the boundary layer. Sampling rates of as high as 100,000 samples/sec can be achieved and record lengths of up to 4096 readings per channel can be acquired per 2-channel unit. Data acquisition is controlled with a PC using software written in C. Equipment at the Wright Labs. is similar. It is described in detail by Simon and Volino (1994).

Power spectral Density (PSD) measurements may also be taken in regions where the flow is not reversing. Such data are acquired in three sections. The first section is acquired with a 100 kHz sampling rate and low-pass filtered at 10 kHz. The second section is acquired with a 10 kHz sampling rate and low-pass filtered at 1 kHz. The third section is acquired at 1 kHz with low-pass filtering at 100 Hz. For each section, 20 traces of 4096 points are digitized. Acquiring the spectra in sections allows better resolution of both high and low frequencies, maximizing the quality of the spectrum, given the limited amount of data that can be acquired and stored in the digitizer for each record. Instrumentation for PSD measurements is similar whether at the University or the Wright Lab. Spectral measurements have proven useful in past work for differentiating between badly-disturbed, non-turbulent flow and flows with turbulence production at the wall.

The approach flow turbulence levels and PSD for three components of velocity, streamwise, cross-stream, and spanwise, have been taken using a TSI Model 1299BM triple-sensor, hot-film probe. An example of these data is shown in Fig. 5. Integral length scales computed from these three spectra are 2.6, 2.1, and 2.2 cm for u, v, and w velocity components, respectively.

Status of the Program

At Wright Labs.

The entire test facility has been modified to include the new airfoils and the new turbulence generator. The new wake generator has been fabricated but the test program is not sufficiently far along for the generator to be installed in the tunnel. The new airfoils have been instrumented with static pressure taps. A sheet with surface-mounted thin-film sensors has been fabricated and is ready for implementation when the program is ready for it. The thin-film sensor sheet has 30 hot-film elements attached to bus wires. The wake generator slider mechanism, the device which drives a row of cylinders or airfoils ahead of the test section, has been designed, constructed, and partially qualified. A photo-diode device to create a trigger signal for the data acquisition has been constructed and checked out. All data acquisition methodology and software has been formulated, transferred to Wright Labs. personnel, and implemented. The tunnel modification is complete. The tunnel has been adjusted to minimize non-uniformity of flow from one passage to the next and non-uniformity of the approach flow. The approach flow characteristics are now suitable. The aspect ratio of the blades is 1.0 which results in an influence of the endwalls on the flow. It seems that this influence may even extend to the centerspan in some cases, thus, careful attention to this effect is needed. Both of the

present investigators have visited the Wright Labs. twice during the period of this grant to take part in the qualification of this tunnel and the senior investigator visited a third time for continued qualification. Qualification visits first entailed the assembly of the facility and acquisition of preliminary check-out data along with the transfer to Wright personnel of instruction about the installed software. Later visits involved measurements and rig modification to achieve improved uniformity and attempts at dealing with the small aspect ratio effects by manipulation of the flow with boundary layer fences. At the Wright Labs., Dr. Richard Rivir and Chris Murawski have continued with the development and qualification. Aside from the aspect ratio concern, the facility is now ready to go and pressure profile data have been taken.

At the University of Minnesota

The University of Minnesota work first involved the reconstruction of a wind tunnel for use with the low-pressure turbine. This was done in conjunction with a low-Reynolds-number program under NASA funding. The tunnel is now complete with the installation of a turbulence generation system and a representative low-pressure turbine airfoil shape. A wake generator fashioned after the Wright Lab. design is presently being fabricated and will allow introducing wakes to the flow. It will be ready for the test program late this Spring. Thus far, the tunnel has allowed a study of the effects of Reynolds number and turbulence intensity on the pressure profile. Careful documentation of the flow with spectral measurements of the three components of the approach flow turbulence is underway. Such measurements include documentation of the decay of turbulence, as needed by computational persons. It is hoped that not only will the data on flow stability from these two rigs be informative in their own right, but the measurements will represent a complete and accurate data set for judging analytical and numerical design methodology. Presently, the approach flow documentation is being completed and a program for measurements within the boundary layer is being charted.

Results to date:

Pressure profiles have been documented for the cases shown in Table 1. These are represented by the cases shown in Figs. 6 and 7. Chord Reynolds numbers presented herein are based upon axial chord length and inlet velocity. For reference, the three Reynolds numbers in Fig. 6 would be 54,000, 98,000 and 196,000 if based on exit velocity and suction surface length. Figure 7 shows that a low Reynolds number case can be dramatically influenced by the level of free-stream turbulence intensity. The highest TI case (10%) appears to be free of boundary layer separation except for a small possible bubble at 80% of chord length. As the turbulence level is

reduced to 3% the separation zone grows to include, it appears, the length $75\% < x/c < 85\%$. Finally, at the lowest value of turbulence, <1%, the separation zone has grown to last 45% of the chord length. Of course, these statements are speculative at this point for we wait for detailed measurements within the flow to confirm that the variations of static pressure represent separation and not some other effect such as a change in the process by which the boundary layer is passing through transition. In Fig. 6 three cases of different Reynolds number are compared for one turbulence level, 3%. Here one can see that as the Reynolds number drops to 40,000, a small separation bubble emerges, and, as it drops further to 22,000, this bubble enlarges considerably, apparently consuming the range $60\% < x/c < 90\%$. Again, more will be learned about these traces when detailed boundary layer measurements are taken.

Summary

The sponsored extension program has allowed opportunities to travel to Dayton for assembly, experimentation, and transfer of information and has allow additional development at the University of Minnesota. The turbulence generation and wake generation development at Wright Labs. has been implemented into the Minnesota program and the instrumentation developed at Minnesota has been implemented into the Wright Lab. program. The communication will continue via e-mail, fax, and phone, now that the close link has been established. In a recent review meeting on the low-pressure-turbine efficiency problem at the NASA Lewis Research Center, the two programs were reviewed before a group of researchers and industry representatives. During the proceedings, it became clear that the two projects discussed herein are highly complementary and that both are major cornerstones to the concerted efforts in the U.S. today on the problem.

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Table 1 Cases for which pressure profiles have been measured in the Minnesota facility.

		Re			
		22,000	40,000	80,000	120,000
TI	0.8%	X	X	X	X
	3.1%	X	X	X	
	10%	X	X	X	

Note: Reynolds number, Re, is based on inlet velocity and axial chord length

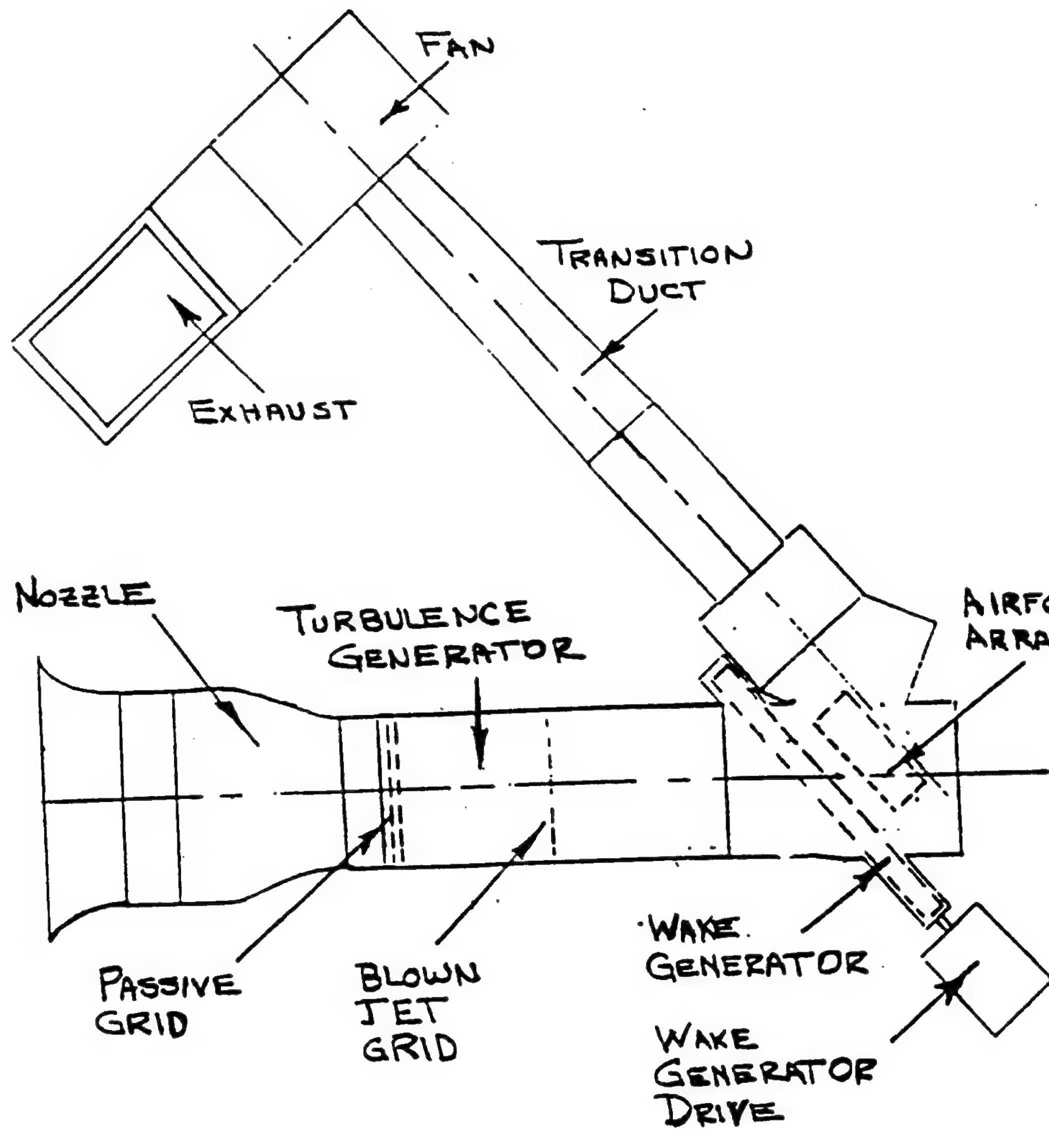


Figure 1 Plan view of the AFIT cascade tunnel at Wright Labs.

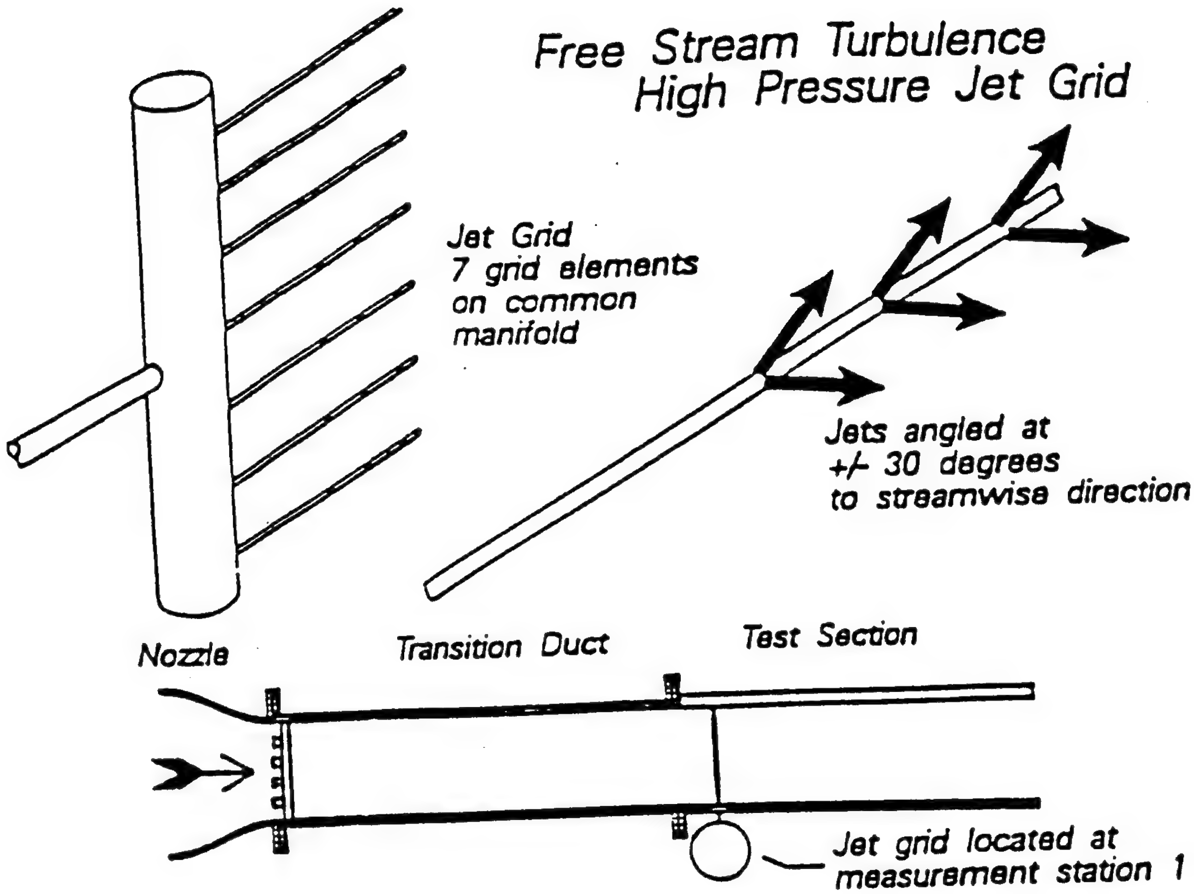


Figure 2 Schematic of the jet grid. From Sahm and Moffat, 1992.

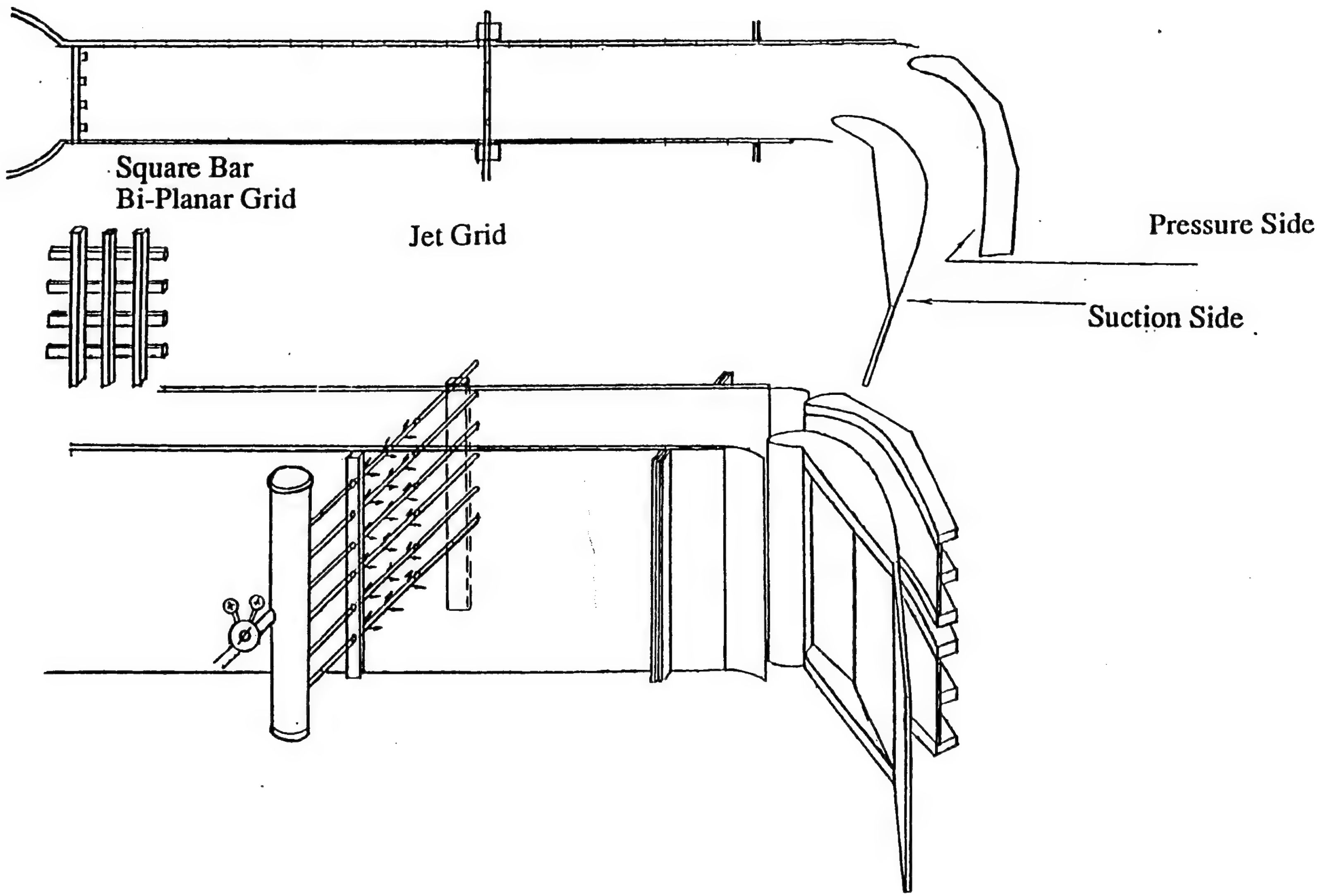
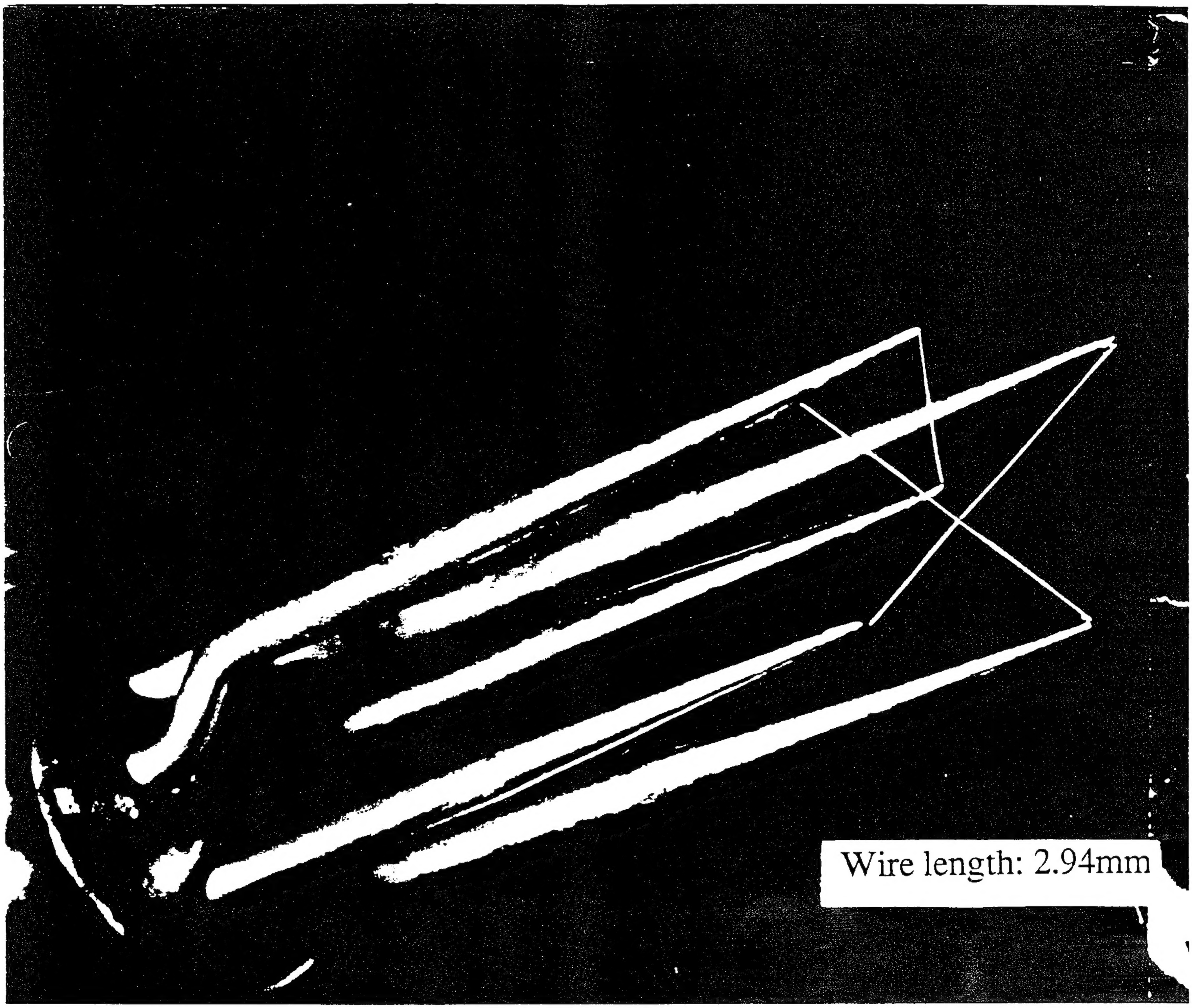


Figure 3 Turbulence generator and test section for the University of Minnesota facility.

Figure 4 Triple-wire probe for measuring three components of velocity and all components of the Reynolds stress tensor.



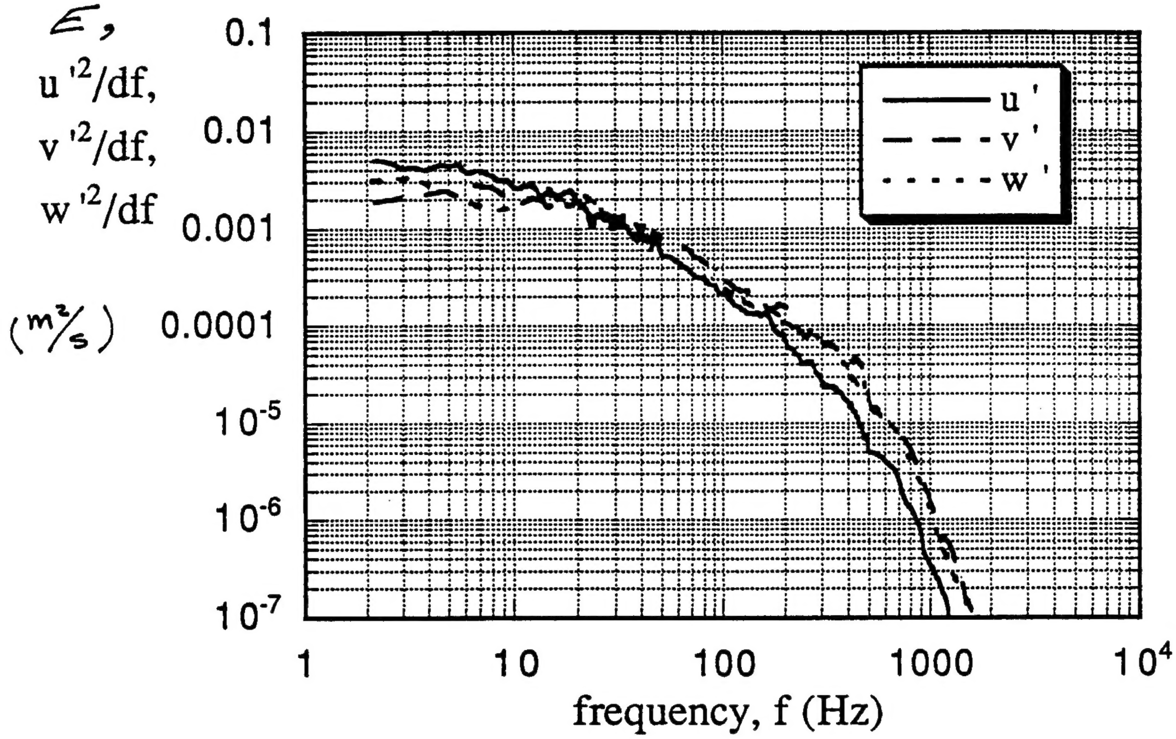


Figure 5 Spectral data taken in the approach flow of the Minnesota facility.

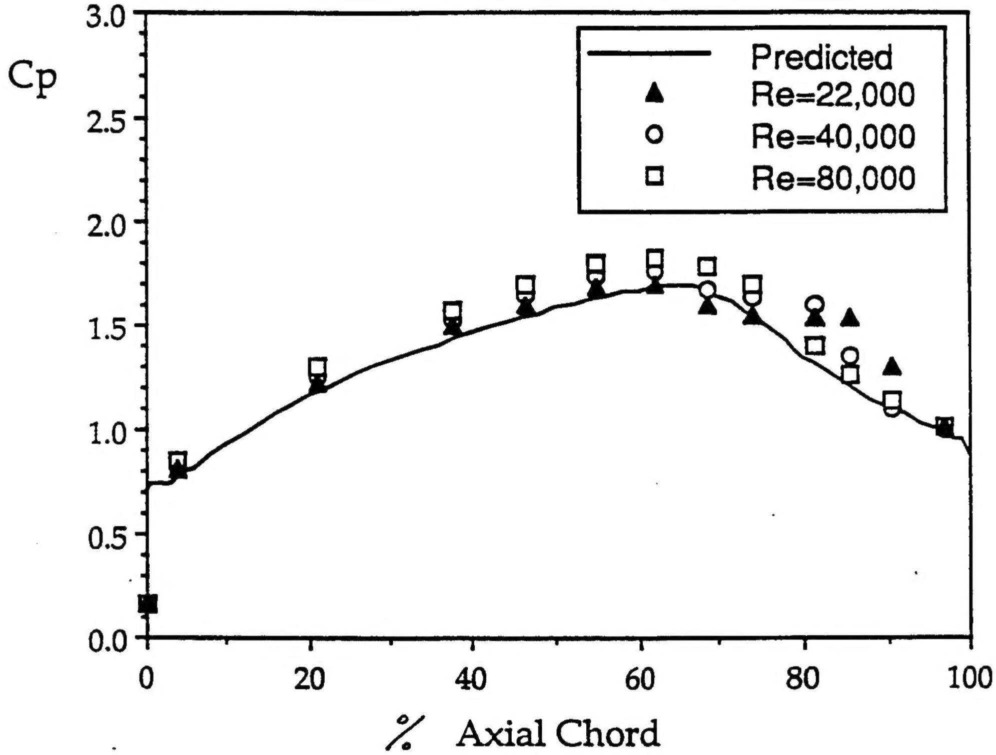


Figure 6 Pressure profiles for various chord Reynolds number values with a single free-stream turbulence intensity (3%).

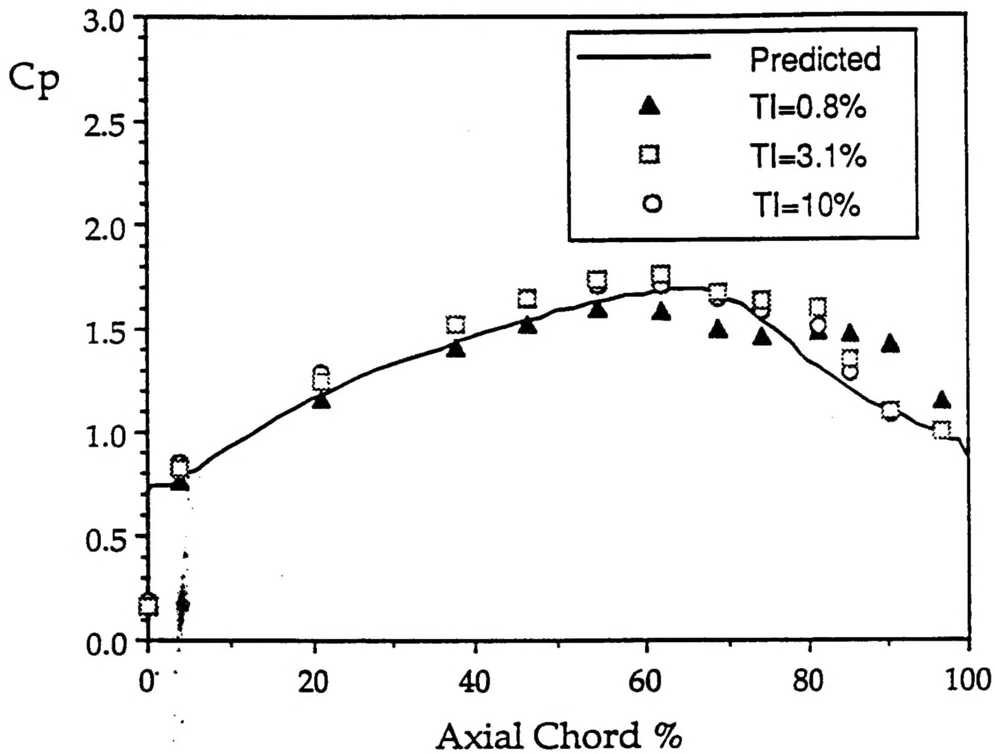


Figure 7 Pressure profiles for various free-stream turbulence intensity values with a single chord Reynolds number (40,000).